

Modelling of multiphase flow in concrete cells of the radioactive waste storage facility at El Cabril (Spain)

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Abstract El Cabril is the low and intermediate level radioactive waste disposal facility for Spain. After sealing the cells that stored the radioactive waste, water was collected from a drainpipe, indicating flow of water within the cell. A hypothesis had been proposed to explain this phenomenon which consists of capillary rise from groundwater and evaporation and condensation within the cell produced by temperature gradients caused by seasonal temperature fluctuations outside. To corroborate this hypothesis a 2D numerical model was made taking into account all relevant processes such as multiphase flow and heat transport. Data were used measured by sensors in the cells and data from laboratory test. There is a good agreement between the temperature measured by the sensors and the ones calculated by the model. The model shows a drying of the concrete at the hot side (that is the wall during summer and the container during winter). The concrete is saturated with water at the cold side (that is the container during summer and the wall in winter), leading to runoff of water to the drainpipe. The flux at this drainpipe occurred in the two yearly periods, being higher in winter than in summer.

1. Introduction

El Cabril is the low and intermediate level radioactive waste disposal facility for Spain, situated in Cordoba (South of Spain). The waste is stored in metal canisters, which are put in concrete containers, which in turn are placed in concrete cells. There are 28 storage cells; each with a storage capacity of 1000 m³ of waste. After filling, each cell is sealed with a concrete slab at the top. In the future when all cells are filled the whole facility will be covered by layers of clay and sand. After sealing the cells, water was collected from drains, installed at the centre of each cell, indicating flow of water within the cell. This occurred during two dis-

tinctive periods each year: summer and winter. Several hypotheses were suggested in order to explain this phenomenon. One of them was related to the rainwater, but there are no correlation between the rain and the periods of the outcoming water from the cell. Another one was that water infiltrates the cell through the junction of the concrete, but the junction could not give that quantity of water collected in the drain. Finally, the hypothesis proposed to explain this phenomenon consists of capillary rise from groundwater and evaporation and condensation within the cell, produced by temperature gradients caused by seasonal temperature fluctuations outside. A key factor is a 2 cm gap between the wall of the cell and the containers with the radioactive waste.

It is known that concrete in constructions and buildings, exposed to variations of temperature and relative humidity could be damaged and its service life reduced by processes involving water flow, heat transport, evaporation and condensation. Several studies can be found in the literature that investigate these processes. Andrade et al. (1999) studied experimentally the influence of daily and seasonal variations inside the concrete. Häupl et al. (1997) found transport parameters coupling the heat transfer, gas and humidity in materials used in construction by means of numerical models. Lü (2002) made a numerical model to predict the heat transfer and humidity in buildings, which has been tested in real buildings. Liu et al. (2004) developed a method to solve condensation problems using numerical models and experimental data.

In relation to the water collected at the cells of El Cabril, several studies have been conducted. Saaltink et al. (2005) made a 1D model in order to corroborate the hypothesis mentioned before, which could reproduce the outcoming water flux from the drains. However, this was too simplified and could only be used for qualitative interpretations. Later, Massana and Saaltink (2006) made a 2D model taking also into account the geometry of the cell. These studies were published by Zuloaga et al. (2006). Saaltink (2006) also made numerical models in order to give possible remediation in the cells. Also, Gamazo et al. (2007) made numerical models that also simulated the cells with a long-term cover. Finally, Ayora et al. (2007) made a 1D reactive transport model in order to study the chemical reactions produced during the concrete alteration.

The models that have been made of the radioactive waste storage cells of El Cabril are hypothetical. They do not use real data of temperature and relative humidity from the cells. Moreover, the hydraulic parameters used by the models are from literature. The objective of this work is to make numerical models of the cells using the data of temperature and relative humidity measured by sensors situated inside and outside the cells. Also we used thermo-hydraulic parameters of the concrete used to build the cells, which have been obtained from experimental test.

2. Conceptual model and governing equations

Figure 1 displays the conceptual model that explains the phenomena observed in the storage cells of El Cabril. Each concrete cell is 3 meters buried into the underlying rock and the rest of the cell is exposed to the atmosphere. The temperature inside the concrete cells (containers) is always 20°C. Outside the temperature oscillates between around 40°C in summer and around 5°C in winter. Between the containers and the wall of the cell a gap of air exists of 2 cm. There is a capillary flux from the water table to the wall of the cell, as the underlying rock and the wall of the cell are hydraulically connected. In summer, the wall is hot and the containers are cold. As a result water ascends from the water table through the wall and evaporates. The water vapour diffuses through the air gap and condenses at the colder containers. Consequently, water runs off to the drain. In winter, the wall is colder and the container is hotter, so water evaporates in the container and condenses at the wall, with water again running off to the drain. This only occurs in summer and winter because only then the temperature difference across the air gap is large enough to produce this phenomenon.

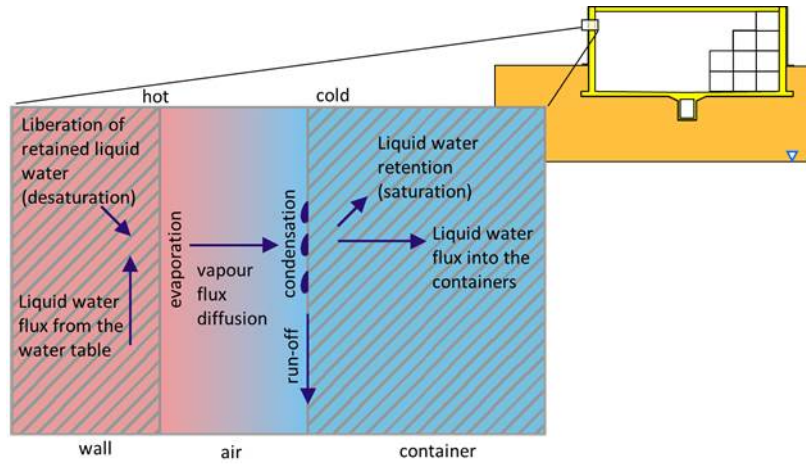


Fig. 1. Conceptual model, scenario in summer (Saaltink et al. 2005).

In order to simulate these processes we used CODE_BRIGHT, a finite element computer code that can model multiphase flow and heat transfer (Olivella et al. 1996). This code solves the water, gas and energy balance equations (Table 1). For more details on each equation we refer to Olivella et al. (1994).

Table 1. Balance equations solved by CODE_BRIGHT (Olivella et al. 1994)

Mass balance of water	$\frac{\partial}{\partial t}(\theta_l \omega_l^w \rho_l + \theta_g \omega_g^w \rho_g) + \nabla \cdot (\mathbf{j}_l^w + \mathbf{j}_g^w) = f^w$
Mass balance of air	$\frac{\partial}{\partial t}(\theta_l \omega_l^a \rho_l + \theta_g \omega_g^a \rho_g) + \nabla \cdot (\mathbf{j}_l^a + \mathbf{j}_g^a) = f^a$
Energy balance	$\frac{\partial}{\partial t}(E_s \rho_s (1 - \phi) + E_l \rho_l S_l \phi + E_g \rho_g S_g \phi) + \nabla \cdot (\mathbf{j}_c + \mathbf{j}_{Es} + \mathbf{j}_{El} + \mathbf{j}_{Eg}) = f^e$

Subscript means phase (l =liquid, g =gas and s =solid); superscript means component (w =water and a =air); θ_α =volumetric phase content ($\theta_\alpha = \phi S_\alpha$); ω_α = water or solute mass fraction in liquid or gas phase (kg kg^{-1}); ρ_α = density (kg m^{-3}); ϕ = porosity; j = mass flux of component in each phase ($\text{J s}^{-1} \text{m}^{-2}$); E_α = internal energy per unit of mass for each phase (J kg^{-1}); S_α = water saturation; f = external supply of component.

A 2D numerical model has been built. Its geometry represents the cell as a cylinder, its volume being equal to the real rectangular cell. This vertical section takes into account: the wall, the containers, the gap of air between the wall and the containers and the underlying rock. A temperature of 19°C in the entire cell has been considered as initial condition, and the initial liquid pressure decreases gradually from the water table (0.1 MPa) to the base of the cell (-0.9 MPa). Table 2 shows the boundary conditions that have been used. The temperature has been fixed and varies with time at the wall and the roof of the cell, using the daily average temperature measured by the sensors situated outside the cell. A leakage boundary condition has been applied to the gap of air between the wall and the container allowing water to leave the cell only when liquid pressure exceeds atmospheric pressure. This represents the runoff water to the drain. Finally, at the bottom of the model the water table is simulated by fixing the liquid pressure to 0.1 MPa.

Table 2. Boundary conditions used in the numerical model.

Mixed boundary condition	$T = T_{atm}(t)$
Leakage boundary condition	$\begin{cases} q = \gamma_l (P_{atm} - P_l) & \text{si } P_l \geq P_{atm} \\ q = 0 & \text{si } P_l < P_{atm} \end{cases}$
Prescribed liquid pressure	$P_l = P_{atm}$

j_e = energy flux ($\text{J s}^{-1} \text{m}^{-2}$); γ_α =coefficient used to prescribe the temperature or the liquid pressure; T =temperature (°C); q = flux of run-off water ($\text{m}^3 \text{m}^{-2} \text{s}$); P_{atm} and P_l = atmospheric and liquid pressure respectively.

Table 3 shows the thermo-hydraulic parameters of the concrete used in the numerical model. Porosity and intrinsic permeability were measured experimentally (Villar et al., 2009). The retention curve, tortuosity, relative permeability and thermal conductivity have been obtained from Massana and Saaltink (2006).

Table 3. Thermo-hydraulic parameters used in the numerical model.

Porosity	$\phi=0.17$
Intrinsic permeability	$k_i=4.2 \cdot 10^{-18} \text{ m}^2$
Retention curve (van Genuchten model)	$S_e = \left(1 + \left(\frac{P_g - P_l}{3} \right)^{\frac{1}{1-0.3}} \right)^{-0.3}$
Relative permeability (van Genuchten model)	$k_{rl} = \sqrt{S_e} \left(1 - \left(1 - S_e^{1/0.3} \right)^{0.3} \right)^2$
Tortuosity factor	$\tau=1$
Thermal conductivity	$\lambda=1.56 \text{ w/mK (concrete wall)}$ $\lambda=3 \text{ w/mK (concrete container)}$

3. Results and discussion

Figure 2 displays the results obtained from the numerical model. In order to measure the temperature of the wall and the container sensors have been installed in the gap of air between wall and container at 3.5 m from the base of the cell, one of them is the wall side and another one at the container side. Another sensor is located in the drain measuring the temperature inside the cell. Figure 2a shows the evolution of temperature measured by the sensors and calculated by the model. Two periods every year could be distinguished: summer where the temperature is around 30°C and winter where the temperature is around 10°C. The temperature at the wall has larger amplitude than that of the container, which means that the wall is hotter in summer and colder in winter thus causing a temperature difference. There is a good agreement between the model results and measured data by the sensors. The temperature inside the cells is displayed in Figure 2b, which varies between 19 and 22 °C. The model can reproduce this variation with the same amplitude but there is some retardation.

Figure 3a displays the saturation of the wall and the container calculated by the model. Similarly with temperature two periods of time every year can be distinguished. In summer, the wall has low saturation (around 0.6) and the container reaches complete saturation. The reverse occurs in winter. This verifies the hypothesis explaining the water coming out of the cell. Figure 3b shows the flux coming out of the cell and the phreatic level, calculated by the numerical model. Again the two periods of time (summer and winter) are distinguished. Water from the water table enters the cell; the largest being in summer. Run-off water leaves the cell also in two periods with large fluxes in winter and small fluxes in summer only in the first two years. The model does not reproduce the measured fluxes of water leaving the cell very well; it overestimates this flux in winter and underestimates it in summer. This could be due to errors in the initial condition which is

not perfectly known or due to the thermo-hydraulic parameters because a calibration is necessary in order to obtain a better fit. Another explanation could be the simplicity of the geometry. Non-cylindrical vertical 2D models of the N-S and E-W section (not shown in this article) could simulate these fluxes better, though they worsen the temperature inside the cell.

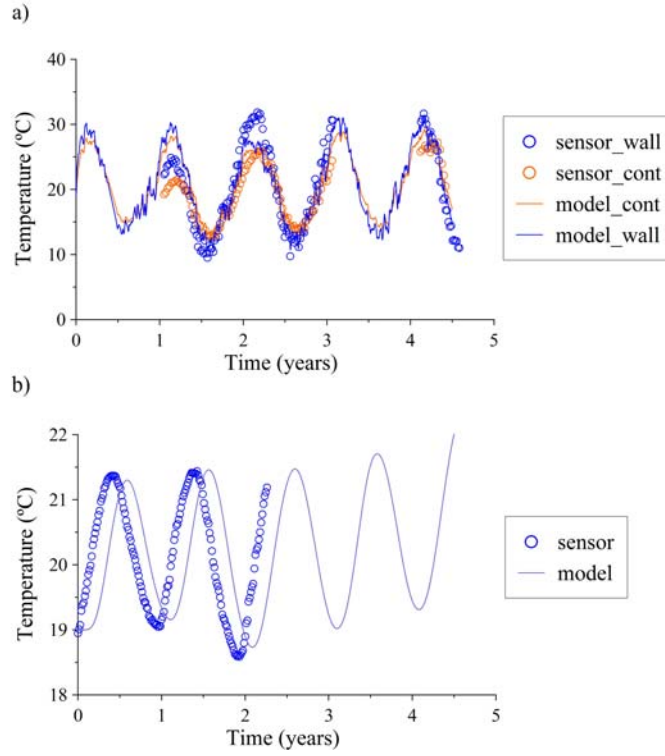


Fig. 2. Results of the numerical model: a) temperature of the wall and the container; b) temperature inside the cell. Lines are the model results and points are the data measured by the sensors.

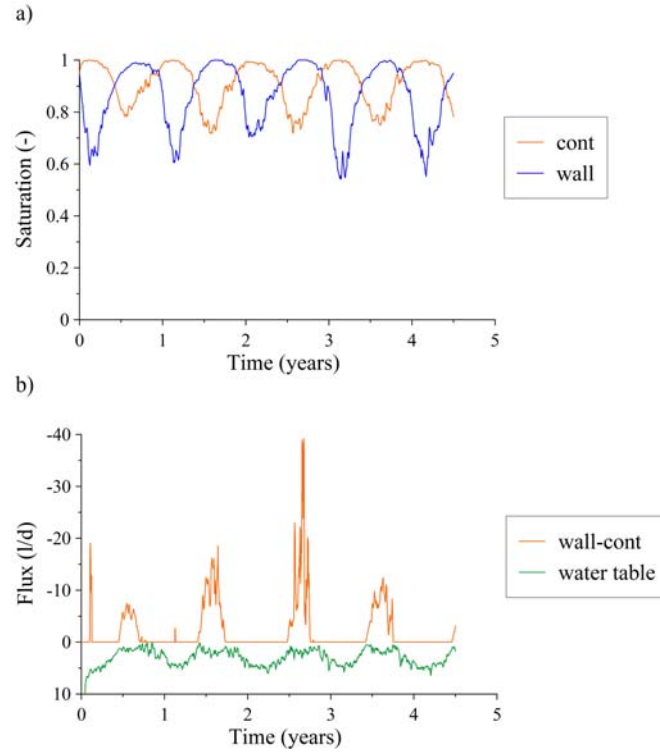


Fig. 3. Results of the numerical model: a) saturation of the wall and the container; b) flux of run-off water, negative values denote outcoming water and positive values incoming water.

4. Conclusions

A 2D numerical model has been presented in order to verify the hypothesis explaining why water comes out of the radioactive waste storage cells of El Cabril after sealing them. The temperature calculated by the model has a good agreement with the temperature measured by the sensors inside the cell. The saturation calculated by the model shows that in summer the wall is drier (around 0.6) and the container is saturated (around 1). The reverse happens in winter. This corroborates the fact that the evaporation is produced at the hot side (the wall in summer and the container in winter) and condensation is produced at the cold side (the container in summer and the wall in winter). The model also reproduces qualitatively that water comes in from the water table and comes out of the cell from the gap of air between the wall and the container. To conclude this work, the model verifies

the fact that water can come out the radioactive disposal cells due to evaporation and condensation processes inside the concrete. However, the model needs more calibration in order to obtain better results.

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